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Wave Runup, Extreme Water Levels and the Erosion of Properties Backing Beaches

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ABSTRACT

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A model has been developed to evaluate the susceptibility of coastal properties to wave induced erosion. The model includes analyses of the probabilities of extreme water levels due to tides affected by various oceanographic and atmospheric processes, and the runup elevations of storm waves on beaches. The application is to the Oregon coast where measured tides often exceed predicted astronomical tides by tens of centimeters, especially during the occurrence of an El Niño. The measurements of wave runup on dissipative beaches typical of the Oregon coast depend primarily on the deep-water significant wave height, but when combined with other data sets show some dependence on the wave period and beach slope. Predicted extreme water elevations due to the combined processes are compared with measured elevations of the junctions between the beach face and the toe of foredunes or sea cliffs. The objective is to evaluate the frequency with which water can reach the property, providing an evaluation of the susceptibility to potential erosion. Application is made to a number of sites along the Oregon coast, revealing differences between the various littoral cells depending on the quantity of sand on the beach and its capacity to act as a buffer from wave attack. A more detailed application is made to the Newport Littoral Cell, demonstrating how this type of analysis can aid in making coastal management decisions. Although the application here is to the Oregon coast, the model can be used on other coastlines with evaluations of extreme tides and storm-wave runup specific to those locations.

ADDITIONAL INDEX WORDS: *coastal erosion, coastal management, ocean waves, tides, wave runup, Oregon.*

INTRODUCTION

Erosion of homes, motels and other properties backing beaches, whether they are in foredunes or sited atop sea cliffs, depends on the elevation achieved by the water relative to the elevation of the fronting beach. The water level depends on predicted astronomical tides, and the many oceanographic and atmospheric processes that alter the mean water level from the predicted tidal elevation. In addition, there is a rise in water level produced by waves, including the setup that elevates the mean shoreline position and the runup of individual waves beyond that mean level.

The other factor important to the occurrence of property erosion is the morphology and size of the fronting beach, and its capacity to serve as a buffer between the attacking waves and properties. The overall size of the beach, governed by the quantity of sediment, largely determines its buffering ability, but morphological elements such as the development of rip-current embayments can also locally determine the width of the beach. The morphology of the beach can be characterized as ranging from dissipative to reflective (WRIGHT and SHORT, 1983), depending on the sediment grain size, beach slope, and wave parameters. This classification relates to the dissipation of wave energy, the dynamic response of the beach morphology, and ultimately to the natural capacity of the beach to protect coastal properties.

This paper reports on a model that has been developed to evaluate the susceptibility of coastal properties to erosion by waves, through evaluations of the factors discussed above, including examinations of the probabilities of extreme mean water elevations and the runup of storm waves beyond that mean water level. The application here is to the Oregon coast where long-term measurements of tides and deep-water wave conditions make such analyses possible. Experiments have been undertaken on a number of beaches so that the runup can be related to the local beach morphology and deep-water wave conditions. The application is illustrated for a variety of sites along the Oregon coast, sites that differ in morphology of the fronting beaches and in their abilities to protect foredunes and sea cliffs from erosion. Although the application presented is for the Oregon coast, the model and techniques can be used on many coastlines to evaluate the susceptibility of properties to erosion, and thus can facilitate scientifically-based coastal management decision-making.

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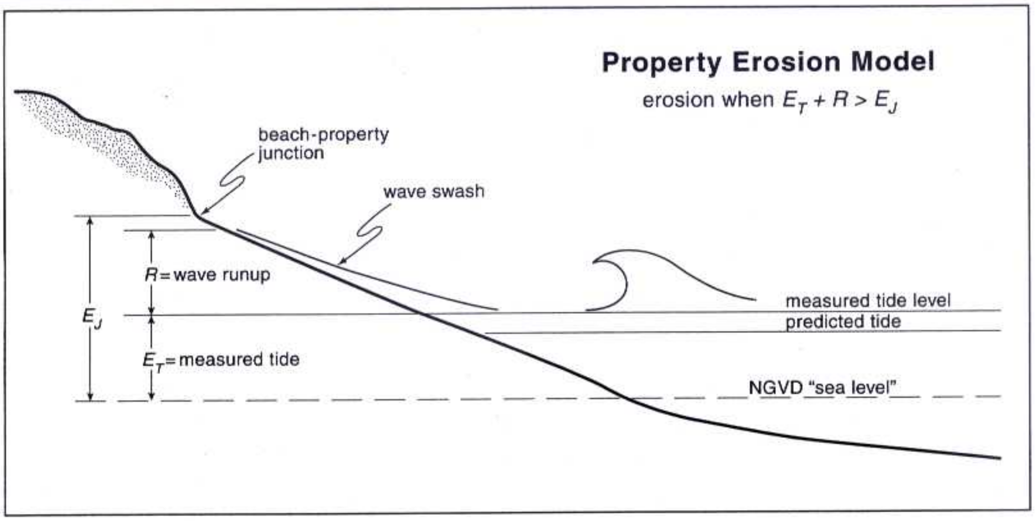


Figure 1. The basic model for the quantitative assessment of the susceptibility of sea cliffs and foredunes to wave-induced erosion.

PROPERTY EROSION MODEL

Wave-induced erosion of properties backing beaches, whether they are in foredunes or sited atop sea cliffs (see Figure 10), depends on the elevation achieved by the water relative to the elevation of the fronting beach. There are two main components, diagrammed in Figure 1, that combine to generate total water levels (SHIH *et al.,* 1994; RUGGIERO *et al.,* 1996; RUGGIERO, 1997). The first is the measured tidal elevation, E_T, which consists of the predicted astronomical tide plus the effects of the many processes that can alter the mean water level. These factors include water temperature, the geostrophic effects of currents, the presence of winds, particularly onshore winds that can cause a storm surge, and the various processes associated with El Niños that alter water levels by tens of centimeters (KOMAR and ENFIELD, 1987; KOMAR, 1998b). Superimposed on these many processes that determine the mean water level at any given time is the vertical component of wave runup, R, consisting of wave setup that elevates the mean shoreline, and swash fluctuations about the mean shoreline position. Wave-induced erosion of a sea cliff or dune will occur primarily when the total elevation of the water at times of maximum runup exceeds the elevation of the beach-face junction, E_J [that is, erosion occurs when $(E_T + R) > E_J$]. Application of the model to evaluate the susceptibility of coastal properties to erosion therefore involves the ability to predict the occurrence of extreme tides (E_T), the runup of waves (R) on the beach during severe storms, and the joint probabilities of these processes.

Data sets containing a decade or more of measurements of wave heights and periods are now readily available for use by engineers, scientists and planners (KOMAR, 1998a). These data, coupled with simple relationships between wave runup and deep-water wave and beach morphology characteristics, suggest a straight forward method of determining extreme runup statistics for a variety of conditions. If the interest is in predicting potential erosion, as in this paper, then empirical relationships for runup statistics are necessary. With a suitable runup model, one can take advantage of measurements of wave heights and periods, and a knowledge of beach morphology, to develop extreme-value distributions of the runup for the particular coastal site of interest.

MEASUREMENTS AND ANALYSES OF WAVE RUNUP

The evaluation of wave runup, defined as the time varying location of the shoreward edge of water on the beach face, has long been important to coastal engineers, oceanographers, and coastal planners (KOMAR, 1998a). Wave runup is a continuous process, but statistics of runup maxima are often the measure of particular interest in engineering applications, and this is the case in the present study.

Based on laboratory data of wave runup obtained by various investigations, Battjes (1974) demonstrated a dependence between the maximum vertical runup elevation, R_{max}, normalized by the deep-water significant wave height, H_s, and the Iribarren "surf similarity" parameter, ξ_o, giving

$$\frac{R_{max}}{H_s} = C\xi_o \tag{1}$$

where C is a dimensionless constant. The Iribarren number is defined as

$$\xi_o = \frac{S}{(H_s/L_o)^{1/2}} \tag{2}$$

where S is the beach slope (equal to tanβ), and L_o is the deep-water wave length given by $L_o = (g/2\pi)T^2$ where g is the acceleration of gravity and T is the wave period. Low values of ξ_o represent relatively dissipative beaches, while high values occur for reflective beaches (WRIGHT and SHORT, 1983). VAN DER MEER and STAM (1992) have compiled the laboratory data on wave runup, particularly on engineering struc-

Table 1. *Environmental conditions during runup measurements.*

Location	Date	# of Runs	H_s (m)	T (s)	S
Gleneden	02/02/91	1	3.2	11	0.047
21st Street	02/17/91	1	2.2	11	0.033
Beverly Beach	03/17/91	1	3.8	15	0.040
Beverly Beach	03/15/94	3	3.0	17	0.040
Beverly Beach	11/16/94	4	4.6	14	0.047
Nye Beach	11/08/95	1	3.3	9	0.030
Nye Beach	11/21/95	3	2.3	7	0.033
Beverly Beach	11/22/95	2	2.0	9	0.037
Agate Beach	(02/07/96–02/17/96)	58	(1.4–4.1)	(5–17)	(0.005–0.025)

tures, and found that it conforms with equation (1) where C depends on the roughness and porosity of the structure.

Using an extensive data set obtained from the intermediate sloped beach of the Field Research Facility (FRF) in Duck, North Carolina, HOLMAN and SALLENGER (1985) and HOLMAN (1986) showed that runup on natural beaches also depends on the Iribarren number according to equation (1). When the runup elevation is expressed as the 2% exceedence value of runup maxima, $R_{2\%}$, it was found that the dimensionless constant of equation (1) is approximately $C = 0.9$. Conditions during which 2% of wave runup maxima reach or exceed the elevation of the beach-face junction are similarly taken in this paper to be a reasonable proxy for potential erosion.

When analyzing a dissipative subset of their data from the FRF, with Iribarren numbers between 0.5 and 1.0, HOLMAN and SALLENGER (1985) found that the incident-band swash is saturated, while the infragravity-band swash increased with increasing offshore wave height. These results were similar to those found by GUZA and THORNTON (1982), who investigated swash dynamics on low-energy dissipative beaches in Southern California. Guza and Thornton suggested a linear relationship between the significant vertical runup elevation, R_s, and the deep-water significant wave height obtaining

$$R_S = 0.71H_S + 0.035 \tag{3}$$

with the units being meters. AAGARD (1990) also found a linear relationship between runup elevation and wave height on relatively low energy dissipative beaches in Denmark and Australia.

We have undertaken field investigations on the central Oregon coast in an attempt to determine predictive relationships for extreme runup, and to further our understanding of runup dynamics on the high energy dissipative beaches common in the Pacific Northwest (RUGGIERO, 1997). All runup measurements were made employing the video techniques developed at the Coastal Imaging Laboratory of Oregon State University (HOLMAN and GUZA, 1984; HOLLAND *et al.,* 1997). Runup time series were extracted from video recordings using the modified "timestack" technique as described by AAGARD and HOLM (1989) and HOLLAND and HOLMAN (1993), in which the landward most identifiable edge of water is digitized using standard image processing algorithms along with manual refinements. Runup was measured under a wide variety of wave conditions; deep-water wave heights ranged from 1.4 to 4.6 m, spectral peak periods ranged from 7 to 17 sec, and a variety of nearshore morphologies were included with beach slopes ranging from 0.005 to 0.047. The field program culminated in February 1996 at Agate Beach in Newport, with a major investigation into the dynamics of high energy dissipative beaches (RUGGIERO, 1997). During this experiment, three video cameras were used with an overlap in the field of view, allowing for continuous coverage of runup measurements over a 1.6 km stretch of beach.

Table 1 lists the locations at which runup measurements were obtained and the environmental conditions during data collection. For each record the tide measured at the Hatfield Marine Science Center in Yaquina Bay, Newport has been removed, and extreme runup statistics have been computed after identifying the local maxima of the runup elevation time series. Although there is a distinction between the processes that force wave setup and swash fluctuations, for most engineering applications the measure of interest is the extreme statistics associated with the total runup. Therefore, all runup statistics presented include both setup and swash. The beach slopes given in Table 1 are specifically the foreshore slopes, taken to be the best linear fit of the measured beach surface between plus and minus two standard deviations from the mean runup elevation. Beach morphology, as well as ground control points used for solving the geometry of the video images, were typically obtained using standard terrestrial surveying techniques. However, during the Agate Beach field experiment, differential global positioning system (DGPS) surveying techniques were employed. This survey system was installed on a 6-wheeled amphibious "buggy" which, by traveling at approximately 5 m/sec, allowed for the dense mapping of a large alongshore beach surface in only a few hours. All wave height and period data in this paper are taken from the Scripps Institution of Oceanography Coastal Data Information Program (CDIP) buoy offshore from Bandon, Oregon, located in approximately 64 m of water. Analyses of wave data from buoys along the coasts of Oregon and Washington demonstate that this CDIP buoy yields results that are representative of wave conditions along the Oregon coast, which is dominated by swell from distant storms (TILLOTSON and KOMAR, 1997)

Several statistical representations of the Oregon runup data have been calculated. The 2% exceedence elevation of runup maxima, $R_{2\%}$, non-dimensionalized by the deep-water significant wave height, is shown in Figure 2 plotted against the Iribarren number. Normalizing the extreme runup data in this

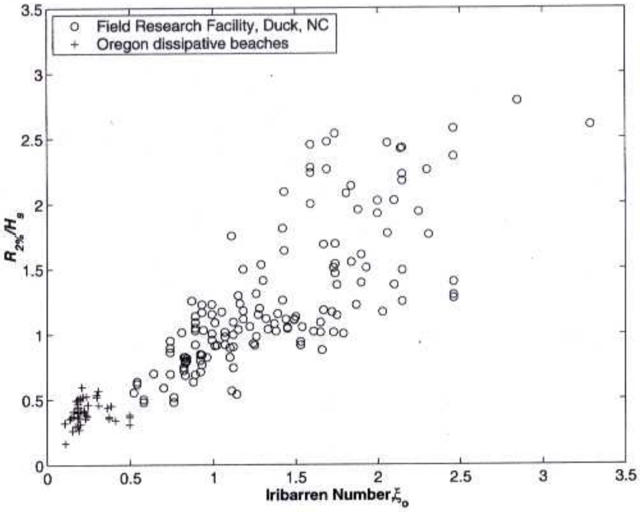


Figure 2. The non-dimensional runup versus the Iribarren number for measurements on Oregon beaches (pluses) and for the data of HOLMAN (1986) from the Field Research Facility, North Carolina (circles).

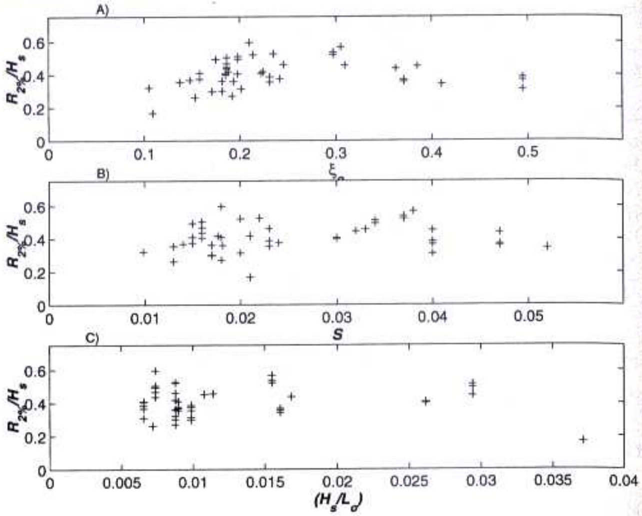


Figure 3. Comparisons between the non-dimensional runup measured on Oregon beaches with the A) Iribarren number, B) beach slope and C) wave steepness.

manner follows the methodology used by Battjes (1974), HOLMAN and SALLENGER (1985), HOLMAN (1986), and several others. The pluses in the figure represent data obtained on Oregon beaches, while the circles are the data of HOLMAN (1986) from the FRF. The Iribarren number clearly distinguishes between the dynamically different nearshore systems of these two sites. The Oregon data fall in the extremely dissipative range of Iribarren numbers, while the FRF data range from dissipative to reflective. Although the Oregon data are of the expected order of magnitude, any linear predictive model forced through the origin and based on Holman's data, would tend to under-predict $R_{2\%}$ on the flatter Oregon beaches, an observation noted earlier by SHIH *et al.* (1994). However, when regressing all of the data (a total of 223 points) against the Iribarren number and calculating an intercept, a linear model performs well in explaining the variance of the data. The slope and intercept calculated for Figure 2, as well as for subsequent data plots, are listed in Table 2.

A close examination of Figure 2 reveals that between Iribarren numbers from approximately 0.25 to 0.75, there appears to be a flattening in the linear dependence between the normalized extreme runup and the Iribarren number. In fact, Figure 3A shows that for the limited and extremely dissipative range of the Oregon data, the non-dimensional $R_{2\%}$ does not depend significantly on the Iribarren numbers ($r^2 = 0.14$). Figure 3B also reveals little dependence of the non-dimensional Oregon runup data on the beach slope S ($r^2 = 0.18$), except at very low values of S. HOLMAN'S (1986) FRF data have been re-analyzed by DOUGLASS (1992), who found that removing the beach slope term from equation (1) does not result in any reduction in the ability to predict runup on intermediate beaches. Similarly, by analyzing a wide variety of Australian beaches, NEILSEN and HANSLOW (1991) found that the relationship proposed by Holman explained results from field experiments on relatively steep beaches with $S >$ 1:10, while for flatter more dissipative beaches with $S <$ 1:10, runup depended only on the wave steepness. In contrast to their results, Figure 3C for our Oregon data shows no dependence of $R_{2\%}/H_s$ on the wave steepness ($r^2 = 0.004$). Although not shown, the dimensional extreme runup does not depend on the wave period, a surprising result as runup has a first-order dependence on the wave period in the dimensional form of equation (1).

All of the Oregon runup data, particularly that on the very low sloping Agate Beach, were dominated by infragravity energy with the peak frequency typically much less than 0.05 Hz (RUGGIERO, 1997). Spectral peaks typically occurred at periods ranging from approximately 100 to 200 sec, and usu-

Table 2. *Regression coefficients for extreme runup statistics.*

Variables	Slope, m	Δ m	Intercept, b	Δ b	r^2
$R_{2\%}/H_S$ vs ξ_o (all data)	0.75	± 0.03	0.22	± 0.29	0.77
$R_{2\%}/H_S$ vs ξ_o (Oregon data only)	0.33	± 0.10	0.32	± 0.08	0.14
$R_{2\%}/H_S$ vs S	3.18	± 0.81	0.32	± 0.07	0.18
$R_{2\%}/H_S$ vs H_S/L_o	0.89	± 1.70	0.37	± 0.09	0.004
$R_{2\%}$ vs H_S (Oregon data)	0.50	± 0.04	−0.22	± 0.21	0.72
$R_{2\%}$ vs H_S (FRF data)	0.42	± 0.03	1.16	± 0.43	0.48
$R_{2\%}$ vs $(b\ H_S\ L_o)^{1/2}$ (all data)	0.27	± 0.004	0.0	± 0.40	0.67

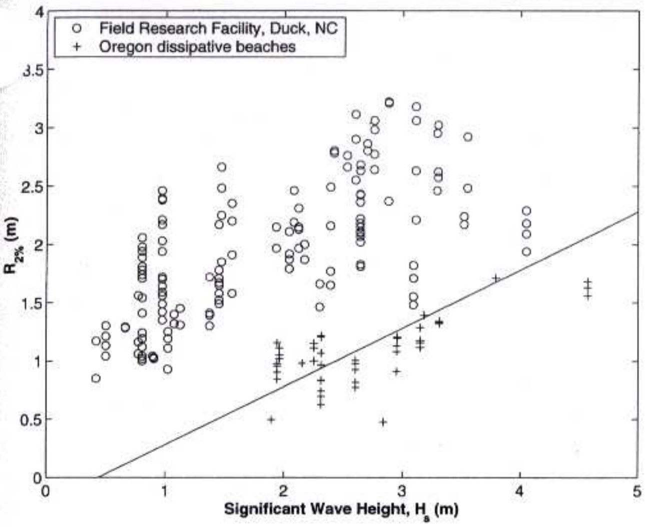


Figure 4. The wave runup, $R_{2\%}$, versus the deep-water significant wave height, for the Oregon data (pluses) and FRF data (circles) of HOLMAN (1986). The straight-line fit to the Oregon data yields equation (4).

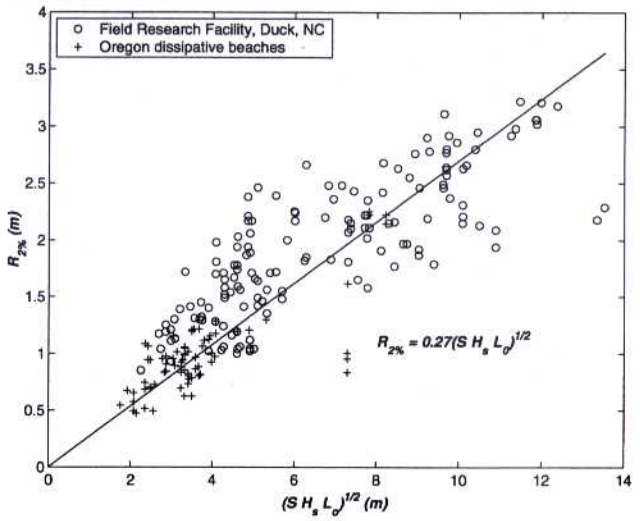


Figure 5. The $R_{2\%}$ runup compared with a relationship that depends on the beach slope $S = \tan\beta$, and on the deep-water significant wave height and wave length, yielding equation (5).

ally more than 90% of the runup elevation variance fell in the infragravity band. The incident band energy was saturated for most data runs. These conditions are similar to those found by GUZA and THORNTON (1982) and AAGARD (1990) on dissipative beaches, and comparable to those stud-`s the best simple parameterization of $R_{2\%}$ for the Oregon ta alone is a dependence on the deep-water significant wave height as shown in Figure 4. The best-fit straight line matched to the Oregon data alone is

$$R_{2\%} = 0.5H_S - 0.22 \tag{4}$$

Thirty-three of the data runs from the Agate Beach field experiment listed in Table 1 are from an analysis of the longshore variability of wave runup over a 1.6 km alongshore distance. Each of these data runs, from the same 2-hour period, have identical offshore wave conditions and only the foreshore slope is a variable. In order not to overly weight the results from Agate Beach where 33 runs were conducted, the alongshore distance has been separated into three regions based on changes in foreshore slope, and averages of $R_{2\%}$ have been calculated for each region. The FRF data of HOLMAN (1986) are included in Figure 4, again to emphasize the fact that the two data sets are derived from dynamically different systems, and the FRF data are clearly offset above the Oregon data. Of interest, within the error estimates of the linear regressions through each individual data set, the slopes of the dependence on H_s are comparable.

Figure 5 shows a final parameterization of wave runup, developed to explain the variance of both the Oregon data and the FRF data of HOLMAN (1986). Convergence of the two data sets requires inclusion of the beach slope S and wave length L_o, but the resulting form is slightly different from the Iribarren number dependence of equation (1). The resulting lationship,

$$R_{2\%} = 0.27(SH_oL_o)^{1/2} \tag{5}$$

is shown as the solid line in the graph of Figure 5, a relationship that performs equally well ($r^2 = 0.67$) in explaining the trends of the Oregon and FRF data.

The three runup relationships, equations (1), (4) and (5), are potentially useful in applications to evaluate extreme runup levels on beaches during major storms, based on measurements of deep-water wave conditions. For this purpose, a 15-year wave data set (1981–1996) from the CDIP buoy offshore from Bandon, Oregon has been used to estimate the extreme wave climate of the Oregon coast. The CDIP measurements, taken in approximately 68 m of water, have been transformed using linear wave theory, to the power equivalent deep-water conditions. A Gumbel extreme value distribution has been fitted to the annual maxima of the deep-water data, and the resulting Figure 6 yields the recurrence intervals for the extreme significant wave heights. Given the relatively short record of wave measurements, predictions of long recurrence intervals have large uncertainties. However, based on the extreme value analyses of this 15-year CDIP data set, the 50-year significant wave height on the central Oregon coast is estimated to be 8.9 m, and the 100-year significant wave height is 9.3 m.

The linear relationship between wave height and runup given by equation (4) can serve to evaluate the corresponding extreme values for $R_{2\%}$ applicable to the dissipative beaches of the Oregon coast; the direct linear relationship between the runup and deep-water wave height yields the $R_{2\%}$ scale given in Figure 6. This scale shows that the 50 and 100-year values of $R_{2\%}$ are respectively 4.2 and 4.4 m. Runup values on steeper beaches, where equation (5) should be used, are still greater for these extreme deep-water wave conditions.

EXTREME MEAN-WATER LEVELS

The other important component in the erosion susceptibility model, Figure 1, is the measured tidal elevation, E_T. Wa-

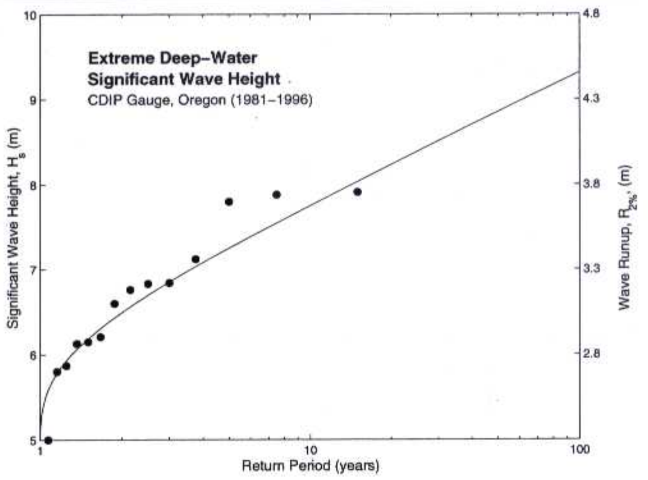


Figure 6. A Gumbel extreme value distribution fitted to deep-water significant wave heights, H_s, measured by the CDIP buoy offshore from Bandon, Oregon. The axis for the equivalent $R_{2\%}$ runup elevations is based on equation (4).

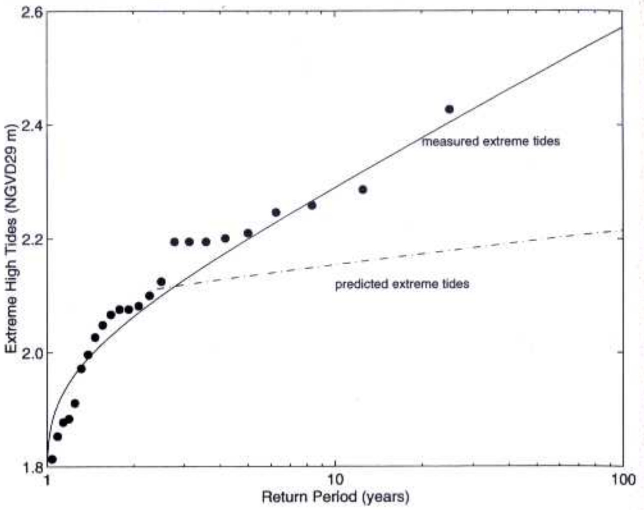


Figure 7. Gumbel extreme value distributions fitted to measured tides (solid line) and predicted tides (dashed line), permitting assessments of extreme tide levels.

ter levels measured by tide gauges are often greater than the predicted astronomical tides due to many processes such as the occurrence of a storm surge, the effects of water temperature, ocean currents, and the occurrence of an El Niño (KOMAR and ENFIELD, 1987; KOMAR, 1998a). A 24-year time series of hourly measured tides (1972–1996) obtained from the tide gauge in Newport has been analyzed to investigate some of these processes and to document the occurrence of extreme tide levels. Elevations reported by tide gauges are typically relative to a tidal datum such as MSL or MLLW, which apply only locally and can vary with time. At the Newport tide gauge, MSL is approximately 10 cm higher than the U.S. National Geodetic Vertical Datum (NGVD) of 1929. NGVD29 has the important advantage of being a nationally fixed reference elevation, therefore most engineering design is relative to this or some other fixed vertical datum (such as NAVD 88). The Statutory Vegetation Line used in Oregon to designate the active beach zone under State jurisdiction is also in terms of NGVD29, and therefore all land and water elevations presented in this paper have been adjusted accordingly to that datum.

The yearly maxima of the measured tides have been fitted to a Gumbel extreme value distribution, and return intervals have been computed for extreme tides. A time series for the predicted tide has been generated for the same 24 year period, using National Ocean Service (NOS) methods, and the predicted yearly maxima have also been fitted to a Gumbel extreme value distribution. Both distributions are shown in Figure 7, and as noted by SHIH *et al.* (1994), for long return periods there are significant differences, on the order of 0.4 m, with the observed extreme tides being higher than predicted.

The difference between measured and predicted tides has been computed for the entire 24-year data set. As a result of the tectonic rise of the Oregon coast, it is not necessary to correct for a relative or eustatic sea-level change (KOMAR and SHIH, 1993). The auto-correlation of the raw tidal residual time series (measured minus predicted tide) shows a roll off in correlation at a lag of approximately 48 hours. This lag corresponds well with the typical storm duration on the Oregon coast. The raw residuals were then filtered using a 48 hour low-pass filter, eliminating measurement noise from the signal. The standard deviation of this low pass filtered residual time series is approximately 13 cm, giving a measure of the typical elevation for storm surge on the Oregon coast. The majority of extreme tidal residuals throughout the 24-year period correspond to times of well-documented El Niño events (RUGGIERO *et al.,* 1996; RUGGIERO, 1997). For example, the 1982–83 major El Niño event raised monthly-averaged water levels by approximately 15 cm above the previously measured high levels for the winter months, and on the order 35 cm above the average measured levels for those months (HUYER *et al.,* 1983; KOMAR, 1986).

TOTAL WATER LEVELS (TIDES PLUS WAVE RUNUP)

The above analyses account for both extreme measured tides and wave runup during major storms, the two components important to sea cliff and dune erosion as illustrated in Figure 1. It remains to add these two processes, which involves a consideration of their joint probabilities of occurrence.

As discussed in the preceding section, the most extreme measured tides along the Oregon coast occur during major El Niño events. Monthly mean wave heights in the Pacific Northwest were shown to be higher than typical during the 1997/1998 El Niño (KAMINSKY *et al.*, 1998). However, our analyses have shown that both the tidal residual and the measured tides are not significantly correlated with wave height throughout the period of overlap between the tide and wave data used in this study, 1981–1996 (RUGGIERO *et al.,* 1996; RUGGIERO, 1997). This observation is significant since it suggests that models such as those proposed by GARES 1990) are not generally suitable to the Oregon coast. In the Gares' model, extreme measured water levels and extreme runup occur at the same time, the experience during hurricanes and Nor'Easters on the East Coast that generate significant storm surge together with high waves. Accordingly, for the Oregon coast it is incorrect to simply add the corresponding extreme occurrences of E_T and R established by our analyses. For example, if the 100-year extreme tide level (E_T = 2.6 m NGVD29) is added to the 100-year storm wave runup (R = 4.4 m), a total water level of 7.0 m NGVD29 is predicted for the extreme combination; however, such an event has a very low probability of occurrence, on the order of 10,000 years if the events are statistically independent as suggested by our analyses.

One can still combine the extreme tides and runup in a rational fashion to yield the expected 50- or 100-year event (KOMAR *et al.*, 1999). For example, a 100-year extreme El Niño might be assessed as the sum of a 50-year extreme tide (E_T = 2.5 m NGVD29) and a 2-year return interval of storm waves (H_s = 7.1 m and R = 3.3 m), yielding a total water elevation of 5.8 m NGVD29. A normal year without the occurrence of an El Niño is better represented by a lower extreme tide, since the processes that generate high water levels are not operating. For a 100-year event during a normal year one might, for example, reverse the significance of the processes; with a 2-year extreme tide E_T = 2.1 m NGVD29 and 50-year storm-wave runup R = 4.2 m, one obtains E_T + R = 6.3 m NGVD29. It is apparent that there is an infinite number of possible combinations of E_T and R to yield 100-year estimated extreme total water elevations. It is possible to examine all combinations to arrive at the most extreme 100-year total water level (KOMAR *et al.*, 1999).

A more useful and direct method for determining the statistics of extreme total water levels, without making the statistically independent assumption, is to apply the model for wave runup to the wave component of the joint time series of waves and water levels. This joint time series is constructed from the time periods during which the wave and water level data overlap. The irregularly spaced wave data have been interpolated to match the hourly measurement interval of the Yaquina Bay tide measurements, and then used to calculate runup at this interval. In doing this we generated a runup time series that can be superimposed on the measured tides to give a 15-year simulated total water level time series. Extreme value analysis is then applied directly to this new time series. In this case, however, the Gumbel extreme value distribution has been produced using all of the water level data above a threshold of 2.8 m NGVD29, rather than just the annual maxima. In doing this, our extremal analysis has combined the Initial Distribution Method (IDM) of VAN VLEDDER *et al.* (1993) with their Peak Over Threshold (POT) method. By performing the analysis in this manner, the return intervals shown in Figure 8A represent the fraction of time when the 2% exceedence elevation of runup maxima, superimposed on the measured tide, reaches or exceeds the elevation of the beach junction, E_J, with the foredune or sea cliff. A threshold of 2.8 m was chosen as this value approximately delineates the tail of the total water level probability distribution function and the elevation at which the extreme probability distribution function becomes valid. Since we have used all of the hourly data above a threshold in constructing the extreme-value distribution, we can convert return intervals to the more convenient unit of hours of wave runup impact per year, which is shown in Figure 8B. As will be seen in the next section, this form of the analysis is particularly useful in assessing the susceptibility of properties to erosion.

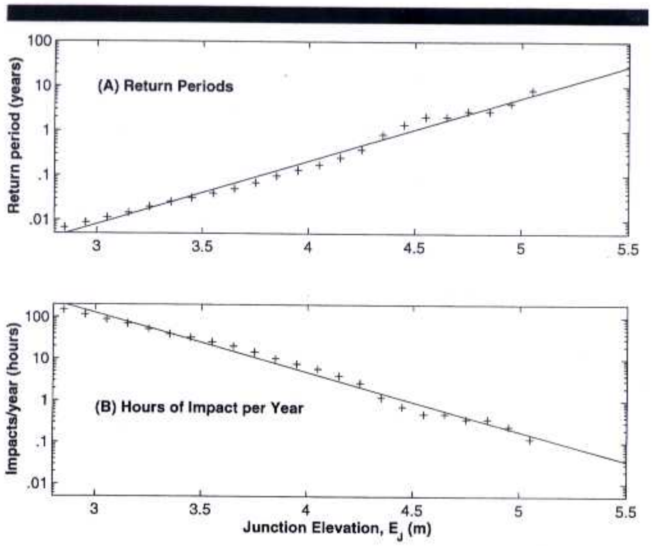


Figure 8. (A) return periods for simulated total water levels determined by combining both measured tides and runup calculated with equation (4) and based on wave measurements. (B) The equivalent hours of wave impact per year during which 2% of runup maxima reach or exceed the elevation E_J.

The two other runup relationships, equations (1) and (5), have also been applied to this direct method of simulating a total water level time series for the period of overlap between the wave and tide measurements. For each of these models, the wave period is needed, in addition to the wave height, in order to determine the deep-water wave length. Also, a beach slope needs to be assumed *a priori* in order to calculate a total water elevation for a particular set of wave height, period and tide measurements. Figure 9 gives estimates of hours of wave runup impact per year for three representative beach slopes; S = 0.01 (pluses), 0.03 (circles) and 0.05 (asterisks). Figure 9A is based on equation (5), and Figure 9B is calculated using equation (1). The results are very similar, with the expected susceptibility to erosion for a particular beach-face junction elevation E_J increasing with increasing beach slope. The results from the simple runup model, equation (4), have been overlaid in both figures as the solid lines, and appear to give similar results as the more involved models if the beach slope is between 0.03 and 0.05. This lends confidence in the simple dependence of runup based on wave height, as much of the runup data collected in this study were from beaches within that range of slopes.

It is important to recognize that the model evaluates the probabilities of wave attack, and that while it is convenient

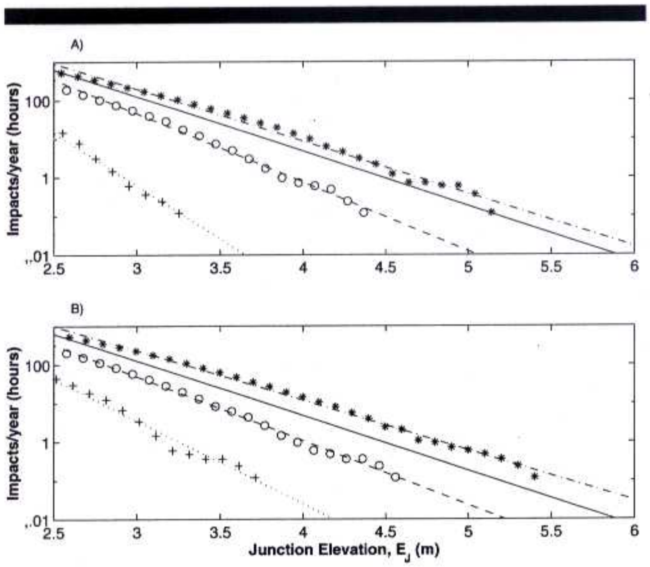


Figure 9. Total water level probability curves calculated with (A) runup model equation (5) and (B) model equation (1), for three representative beach slopes, S = 0.01 (pluses), 0.03 (circles) and 0.05 (asterisks). The solid lines without data points were calculated with the simple runup equation (4).

to express this as the average number of hours per year that waves could reach and impact the property, those values should not be taken too literally. It is apparent that the impact hours per year will vary greatly from year to year for a particular site, and in the application to foredune areas there can be an episode when the dunes are cut back by erosion even though the long-term trend is one of accretion. With further research and refinements in the model, it may be possible to better account for this variability. Such refinements would in particular have to examine variations in the elevation and morphology of the beach. For example, while the annual cycle of beach-profile changes from summer to winter may not significantly change the E_J elevation at the back of the beach, the local presence of a rip current and the embayment it erodes can lower E_J by 10s of centimeters, locally and temporarily enhancing wave impacts and property erosion (SHIH and KOMAR, 1994; KOMAR, 1997). In a sense, there is a probability distribution of E_J elevations at a particular site rather than a specific value, and this probability should be included in the analysis together with the probabilities of extreme total water levels.

APPLICATIONS OF THE MODEL TO THE EROSION OF SEA CLIFFS AND FOREDUNES

The Oregon coast is divided into a series of littoral cells, with beaches confined between large headlands (KOMAR, 1997). The elevation, E_J, of the beach-face junction varies considerably between cells due to differences in quantities of sand, and also due to contrasting beach sand grain sizes and beach slopes (SHIH and KOMAR, 1994). A number of beaches having varying morphologies and buffering abilities have been monitored to determine these elevations relative to NGVD29, as well as to quantify typical summer and winter profiles and long term morphology changes. The erosion susceptibility model has been applied to the 13 sites listed in Table 3 from north to south, accounting for 8 separate littoral cells. More detailed information concerning the study sites is given in Ruggiero (1997). The beaches are backed by sea cliffs, dunes, and at 5 sites by shore protection structures that were investigated by HEARON *et al.* (1996) to determine the impact of such structures on the fronting beach or adjacent properties. All sites have beach slopes within the range of applicability of the runup models derived from data collected in this study.

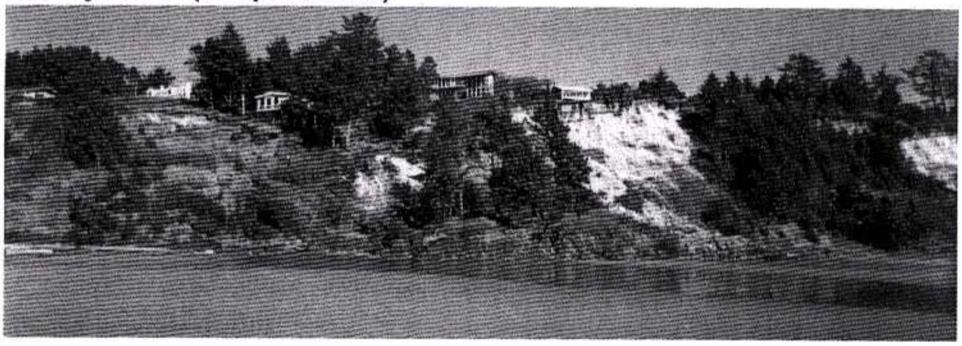
Table 3 summarizes the model results as applied to the 13 sites, having employed each of the three runup models, equations (1), (4), and (5). The average winter beach face junction elevations are seen in Table 3 to range from 2.9 to 7.5 m NGVD29, a substantial range that reflects the different buffering capacities of the fronting beaches. The number of hours per year during which 2% of runup maxima are predicted to reach or exceed E_J are given for the 13 sites, together with an observation column that provides a qualitative assessment of the level of erosion or accretion. Figure 10 contains photographs of representative sites, showing varying levels of erosion or accretion. It is apparent that although qualitative, there is a good correspondence between the calculated

Table 3. *Wave impacts per year as compared to observations of beach stability.*

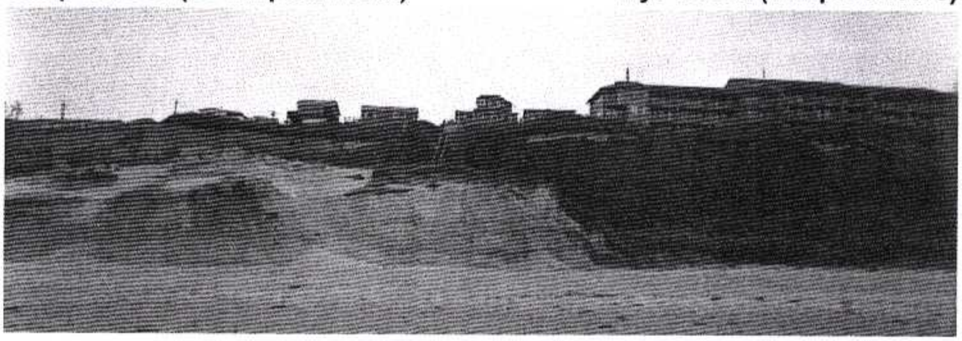
Site	Backing Feature	S	E_J (m)	Impacts Per Year (hrs) (4)	(1)	(5)	Observations
Jump Off Joe	Sea Cliff	0.034	2.9	173	97	104	severe erosion
Nye Beach	Sea Cliff	0.034	3.7	13	5	4	stable
Beverly Beach	Sea Cliff	0.043	4.0	4	7	5	erosion
Oceanside	Dune	0.023	3.6	18	3	2	stable/erosion
South Beach	Dune	0.026	4.1	3	0.3	0.2	accretion
Manzanita North	Dune	0.025	4.2	2	0.2	0.1	stable/erosion
Manzanita South	Dune	0.038	6.3	—	—	—	heavy accretion
Nestucca Spit	Dune	0.046	6.5	—	—	—	heavy accretion
C&L Ranch	Sea Wall	0.030	3.2	77	38	37	severe erosion
Pacific Shores	Sea Wall	0.039	3.7	15	12	10	erosion
San Marine	Sea Wall	0.030	3.8	11	4	3	erosion
Pacific Palisades	Sea Wall	0.052	5.3	—	0.3	0.2	accretion
Driftwood Shores	Sea Wall	0.033	7.5	—	—	—	heavy accretion

Manzanita South (0 wave impact hours)

Beverly Beach (5 impact hours)



Jump Off Joe (104 impact hours) **Nye Beach (4 impact hours)**



Lost Creek (90 impact hours)

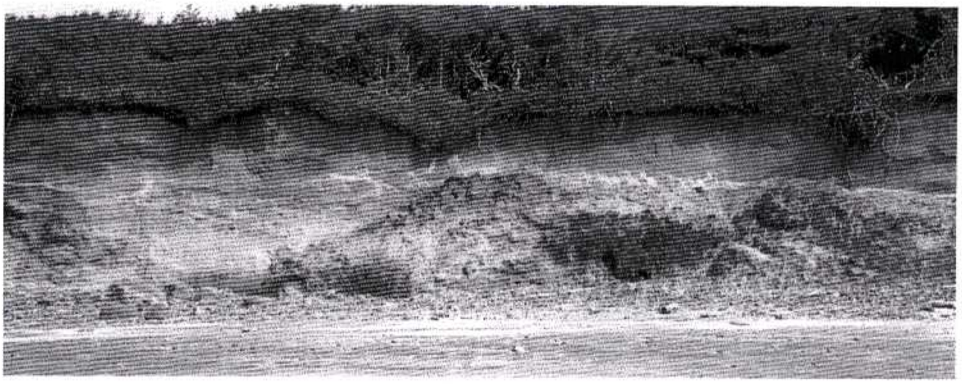


Figure 10. Photographs of sites on the Oregon coast, where the degree of erosion or accretion qualitatively corresponds with the evaluated wave impact ~s listed in Table 3.

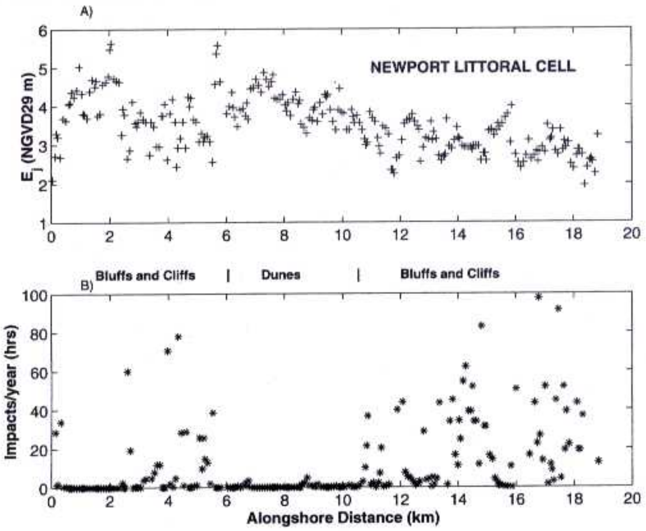


Figure 11. (A) Elevations relative to NGVD of beach-face junctions along the length of the Newport littoral cell, with increasing distance to the south. (B) Model calculations of the expected hours of wave impact per year.

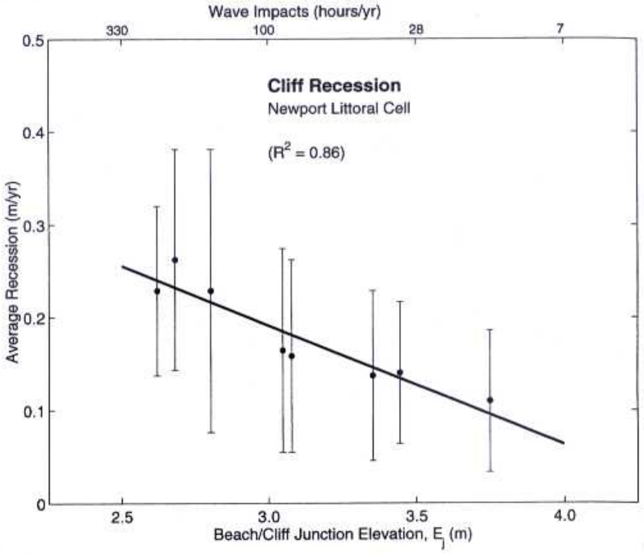


Figure 12. The average rates of sea cliff erosion measured in the south portion of the Newport Littoral Cell, compared with the elevation E_J of the beach/bluff junction and with the average hours of wave impact per year evaluated with the model.

wave impacts per year and the observed level of erosion or accretion. Roughly, it appears that shorelines subjected to less than 1 hour of attack per year tend to be stable or accreting, while those experiencing more than 10 hours per year experience erosion. This result provides some level of confidence in applying the model of Figure 1, with predictions of extreme water levels, broadly to the Oregon coast in evaluations of the susceptibility of properites to potential erosion.

A more detailed analysis has been undertaken of the Newport Littoral Cell, which has a 40 km beach length extending from Yaquina Head on the north to Cape Perpetua in the south. The model has been applied to the northern half of this cell as a test of its potential usefulness in evaluating the susceptibility of properties to erosion as part of a coastal management program. Figure 11A shows the alongshore variation in E_J measured at approximately 50-m intervals (the cell's northern limit, Yaquina Head, is given an alongshore location of 0 km). The beach throughout the cell is backed by a variety of features including sea cliffs, dunes and a few shore protection structures. Foreshore beach slopes also have been measured throughout the cell, all having values less than 0.04 and therefore within the range from which the runup models were derived. Figure 11B gives the computed predictions of the wave impact hours per year, based on equation (5), using local values for E_J and the beach slope. The estimates of the frequency of wave impact reveal the relative susceptibility to erosion along this particular stretch of coastline. For example, the model suggests that the large sand dunes of South Beach, located between 6 and 10 km from Yaquina Headland immediately south of the entrance to Yaquina Bay, are comparatively free from frequent wave attack. Sand dunes respond relatively quickly to erosion, and therefore achieve beach-face junction elevations that are more in equilibrium with the fronting beach and offshore wave conditions, thereby reducing the frequency with which waves reach the toe of the dunes to produce additional erosion. According to the results in Figure 11B, the beaches further to the north and south, backed mostly by bluffs and sea cliffs, experience wave attack much more frequently. These results are consistent with long term observations. Although the sea cliffs and bluffs are impacted by waves more frequently than the sand dunes that have higher beach-face junction elevations, they erode relatively slowly due to their resistance.

Figure 12 compares long-term average rates of sea cliff erosion in the southern part of the Newport littoral cell with the model-evaluated hours of wave impact per year. This segment of shoreline consists of sandy beach backed by bluffs of uniform composition consisting of a basal layer of seaward-dipping Tertiary mudstone capped by consolidated Pleistocene marine terrace sandstone. The cliff recession rates were determined by DOGAMI (1994) using aerial-photo analyses, with each of their values representing approximately 100-meter longshore increments. We have combined their estimates into averages for segments of bluff delineated by creeks that disect the stretch of bluff. The average elevation of the beach/bluff junction was determined for each segment, so the results plotted in Figure 12 are averages for kilometer-scale stretches of bluff. The error bars on the figure represent the standard deviation of the individual measurements for each averaged segment. Although the range of individual measurements is relatively high the average recession rates are seen to form a simple linear trend with the rate of bluff erosion decreasing with increasing junction elevation, E_J, and hours of wave impact per year.

An area of special interest in the Newport Littoral Cell is the Jump Off Joe Landslide at Nye Beach, within the city of Newport. The initiation and major movement on this land-

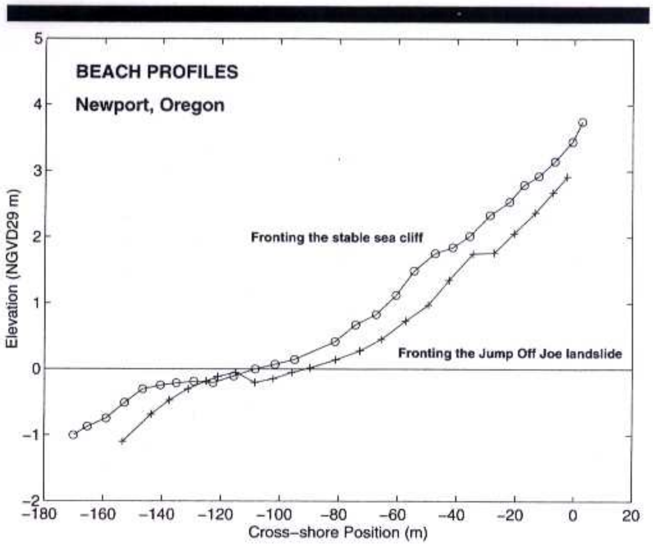


Figure 13. Profiles surveyed during November 1995 in front of the Jump Off Joe Landslide, Newport, and 70 m to the south where the sea cliff along Nye Beach has not been affected by landsliding. The calculated hours of wave impact per year are respectively 104 and 4 (Table 3).

slide occurred during the early 1940s, destroying a number of homes; an attempt to re-develop the site in the 1980s led to the loss of a new block of condominiums (SAYRE and KOMAR, 1988). There has been a slow continued downward and outward movement of the slide block, so the Jump Off Joe Landslide still projects out onto the beach compared with the natural sea cliff at the adjacent Nye Beach (Figure 10). The base of the landslide consists of indurated mudstone that is fairly resistant to erosion, and this accounts for its continued projection out onto the beach. Figure 13 contains two beach profiles surveyed during November 1995, separated by only 70 m in the longshore direction, with one profile fronting the toe of the landslide while the second was obtained in the section of the Nye Beach sea cliff unaffected by the landslide. At that time the landslide extended about 5 m out onto the beach beyond the line of the unaffected cliff, accounting for the horizontal displacements of the two profiles. Of interest, the level of the beach in front of the landslide is lower than the profile in front of the sea cliff. It is possible that the landslide toe is having the same effect as a seawall that protrudes onto the active beach, interacting with the waves to produce toe scour (KOMAR, 1998a). The overall effect is that the elevation E_J at the toe of the landslide (2.90 m NGVD) is lower than at the toe of the sea cliff (3.70 m NGVD) which has not been affected by the landslide. As seen in the results given in Table 3, this seemingly small difference has a marked control on the expected frequency of wave attack; according to the calculations of runup with equation (5), the toe of the landslide should experience about 104 hours of wave impacts per year, while the adjacent sea cliff is affected only about 4 hours per year. This difference is verified by the fact that waves reach the toe of the landslide during most high tides throughout the winter, and are actively cutting back the toe leaving a nearly vertical scarp (Figure 10). In contrast, waves rarely reach the Nye Beach sea cliff, and as a result, the cliff is covered with vegetation and has not experienced significant erosion for over 100 years.

CONCLUSIONS AND DISCUSSION

The focus of this study has been the development of a model to evaluate the susceptibility of coastal properties to wave-induced erosion. Important in the application of the model is the ability to quantitatively assess extreme values of mean water elevations and the runup of waves during major storms.

An analysis of measured versus predicted tides demonstrated that the former can be on the order of 0.4 m higher, so that non-tidal processes affecting mean water levels can be important to erosion along the Oregon coast. The highest water levels and greatest deviations between predicted and measured tides were found to occur during El Niño events, and result from warmer offshore waters, the geostrophic effect on northward flowing ocean currents, and shelf-trapped waves originating at the equator. Of significance, storm surge is less important on the Oregon coast compared with shores dominated by hurricanes, and as a result, the occurrence of extreme mean-water elevations and extreme waves due to major storms are primarily statistically independent events.

The runup of waves on the high-energy dissipative beaches typical of the Oregon coast has been measured under a range of offshore wave conditions and beach morphologies. Unlike runup on intermediate to reflective beaches where the dependence is on the Iribarren number, equation (1), the variance in runup data from Oregon's dissipative beaches was found to be explained simply by the deep-water wave height [equation (4)] or by a modified relationship [equation (5)] that includes some dependence on the wave length and beach slope.

Extreme total water levels, the mean water of the measured tide plus the runup of storm waves, have been predicted by fitting an extreme-value distribution to a simulated total-water level time series. These predictions are used to determine the relative susceptibility of properties backing beaches to erosion. Coast-wide comparions as well as site specific applications on the Oregon coast indicate that the assessments correlate well with qualitative and quantitative observations of degrees of erosion or accretion.

The simulated total water level time series developed in this study extends for the 15-year life of the Bandon CDIP buoy, the buoy used in developing runup relationships (1), (4), and (5). Following the decommissioning of the buoy in 1996 and the completion of this study, the Oregon coast has experienced two extreme winters. The high water levels of the 1997/1998 El Niño and the large waves during the 1998/1999 La Niña, caused extensive erosion throughout the state. Data from these two winters would need to be included in updated projections of extreme events. This example illustrates the necessity of using up-to-date compilations of data on waves and water levels in future applications of the model.

With the model developed in this study, the relative frequency of occurrence of sea cliff or dune erosion can be predicted for most coastal sites using historical wave, tide and beach morphology records. Although the application here has been specific to the Oregon coast, the model can be similarly applied to other coastal areas by making necessary modifications as to how extreme mean-water elevations are calculated and how the runup of storm waves is related to the wave climate. For example, with some modification the model has been used to examine erosion along the coast of Washington (RUGGIERO *et al.,* 1997), to calculate the frequency of wave attack at the toe of a large landslide north of San Francisco (KOMAR, 1998c), and in evaluating bluff erosion along the shores of Lake Hawea on the South Island of New Zealand where water levels are regulated for hydroelectric generation (KIRK *et al.,* 2000).

Coastal management specialists can use the models to quantitatively estimate the expected susceptibility of property to erosion during extreme events, and thus the model serves to establish process-based setback distances for coastal developments (KOMAR *et al.,* 1999). The model can also aid in the development of dune-management plans which balance the role of dunes in reducing future property losses versus development pressures such as those currently being experienced on the Oregon coast. In its present form the model may also be used to evaluate the need for shore protection structures and might assist in their design. Future model development will attempt to include impact forces in order to predict erosion rates of both sea cliffs and foredunes. Although not presently important along the Oregon coast, the addition of the long-term sea level rise to the predicted extreme water levels can be easily accomplished, and will be important at other coastal sites.

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